Common characteristics of feedstock stage in life cycle assessments of agricultural residue-based biofuels

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Abstract: In this study, we conducted life cycle assessments (LCAs) for fuels based on different types of agricultural residues and determined the characteristics common to all LCAs. Each fuel type required specific conversion technology during the feedstock stage, particularly during the production and collection processes. We divided the field-to-fuel life cycle into five high-level and relatively independent sub-stages: production of agricultural residues, collection of agricultural residues, conversion of agricultural residues to biofuels, biofuel distribution, and biofuel utilization. We then illustrated the common characteristics during the feedstock stage for the first two field-to-fuel life cycle sub-stages: production and collection of agricultural residues. Agricultural residues-to-grain weight and price ratios and multifactorial LCA allocations were summarized for the production stage. In addition, the energy use availability coefficient, collection radius, and emissions were determined for each fuel type during the collection stage. System boundaries and benefits of direct emissions reduction during the feedstock stage were also discussed. Our results provide guidance for future LCA studies on agricultural residue-based biofuels.

Keywords: Agricultural residues; biofuels; life cycle assessment; feedstock stage; common characteristics

1. Introduction

The use of renewable energy is gaining more prominence. At present, the development of a low-carbon economy and promotion of green technology are essential to plans for economic and social development. A redesign of energy production and consumption processes is urgently needed to build a clean, low-carbon, safe, and efficient energy system while resolving problems with environmental pollution.

As fossil fuel-based resources are associated with negative environmental impacts and security issues, alternative resources that are more sustainable, such as biomass[1], have to be developed. Biomass fuels can be derived from an abundance of raw materials, including agricultural and forestry residues, livestock and poultry manure, energy crops (plant biomass), industrial organic wastewater, and municipal sewage and garbage. Biomass fuels are not only renewable but like conventional fossil fuels, can also be collected, stored, and transported relatively easily. Biomass energy plays an important role among all kinds of renewable energy, such as wind, solar, hydro, biomass, geothermal, wave, tide and ocean thermal energies. Biomass can be converted directly into chemical products to generate electricity, heat, and fuels. For example, liquid and gas fuels and briquettes produced from biomass can be used instead of petroleum, natural gas, and coal, respectively. The broad-scale use of biofuels can contribute greatly to achieving energy sustainability and reducing greenhouse gas emissions.

Lignocellulosic biomass is one of the most abundant biomass resources on earth, and more than 100 billion metric tons are produced every year. This amount represents a significant feedstock for producing biomass fuels[2]. Approximately 3.7–5.1 billion metric tons of lignocellulosic biomass are produced as part of agricultural residues annually[3–5]. Thus, using agricultural residues to produce energy is an important strategy for achieving renewable energy targets[6]. China is a major agricultural country, producing approximately 0.9 billion metric tons of agricultural residues annually[7]. Although China has abundant agricultural residues, there is a significant wastage of this potential energy resource due to discarding or direct burning in the field, with associated adverse environmental impacts of fine particulate matter, elemental carbon and organic carbon et al[8,9]. Therefore, it is important to use agricultural residues by transforming them into biofuels. These biofuels could then supplement the energy supply and alleviate demand for fossil energy and resources. Biofuels derived from lignocellulosic biomass, particularly from agricultural residues, are recommended worldwide as part of high-level strategies to mitigate climate change, enhance energy security, and develop rural economies[10,11].

Despite their advantage as a renewable fuel source, the conversion and use of agricultural residue-based biofuels have negative impacts on the environment. Although we should pursue the technological development of agricultural residue-based biofuels to improve energy efficiency and use scales, we should also mitigate their environmental and societal impacts. To do that, we must consider energy conversion efficiencies, greenhouse gas emissions, and air pollutant emissions during the production and use of biofuels. Life cycle assessment (LCA) models and methods can be used to guide the development of biofuel technology.

The feedstock stage represents a major process of the life cycle of agricultural residue-based biofuels. Compared with coal, oil, and natural gas, agricultural residues are more scattered, less energy-dense, and less efficient in terms of storage and transportation. Large amounts of agricultural residues are not used further and are burned directly in fields instead. Furthermore, these residues have a low unit price for energy use but are associated with high labor costs for processing. Because agricultural residues can also be used as fertilizers, forage, and industrial raw materials, they garner higher prices for those uses than if they were converted to biofuels. Thus, it is not economically competitive to collect agricultural residues for fuel production. Additionally, agricultural residues are considered waste products or by-products of grain production, and little data on their environmental impacts have been collected. Hence, the utility of processing agricultural residues for biofuels, particularly during the feedstock stage, is not well understood.

Recently, studies have been conducted on the social, economic, and environmental performance of agricultural residue-based biofuels, which were used for power generation[12] and heating[13]. Agricultural residues were also used to make liquid fuels[14,15], briquettes[16], and flammable gases[17,18]. Allocation methods can greatly influence the outcomes of LCAs[19]. For agricultural residue-based biofuels, LCAs can consider global warming potentials[20] and the goals of the production system[21]. Three LCA allocation methods—economic, energy-based, and subdivision—have been developed by Murphy and Kendall[22]. The subdivision method allocates impacts from changes in the system of baseline (corn only) production to stalks. Similarly, economic allocation also assigns impacts to stalks. Allocations using economic and subdivision methods are approximately half of those using the energy-based method[22]. The choice of allocation method can affect the environmental performance of a lignocellulosic biorefinery and the environmental impacts assigned to individual products, both on a unit and annual flow basis[19].

Transformation technologies and LCA results vary for different types of agricultural residues. To our knowledge, there are no detailed studies on the common characteristics across LCAs of different types of agricultural residue-based biofuels. Additionally, very few studies focused on the feedstock stage of the life cycle of agricultural residues-based fuels. In this study, we report the similarities among transformation technologies in the feedstock stage, including production and collection. Environmental impacts were assessed for this life cycle stage as well. The LCA of agricultural residue-based biofuels were divided into five sections below: Section 2 details the LCA stages relevant to agricultural residue-based biofuels; Section 3 focuses on the production of agricultural residues, namely, agricultural residues-to-grain weight and price ratios, and multifactorial allocation; Section 4 focuses on the collection of agricultural residues, with an emphasis on arable land area coefficients of crops, and the energy use availability coefficient, collection radius, and emissions produced during the collection process; System boundaries and direct emission reduction benefit of feedstock stage is discussed in section 5 and section 6, and finally section 7 summarizes the conclusions from the study. The results from our study provide additional information for evaluating policies related to the potential environmental benefits of agricultural residue-based biofuels, and for enhancing the efficiency of using agricultural residues as fuel.

2. LCA stages of agricultural residue-based biofuels

An LCA is a cradle-to-grave assessment of a product or service. During an LCA, the impact any product is analyzed over its lifetime, from the extraction of raw materials to the disposal of waste components and product end use[23,24]. An environmental LCA can be defined as the compilation and evaluation of material and energy flows, and the potential environmental impacts of these flows, throughout the life cycle of a product[25]. An internationally standardized methodology is used to identify and quantify the environmental aspects and potential impacts at each life cycle stage, from obtaining resources and materials, to production, distribution, usage, and final disposal[26]. Life cycle stages are based on the ISO14040[27] and ISO14044[28] guidelines.

According to the ISO guidelines, the life cycle of agricultural residue-based biofuels starts with production and ends with fuel utilization. The collection of agricultural residues, conversion of residues to fuels, and fuel distribution can be treated as distinct periods within the life cycle, and individual characteristics can be assessed for each period. Thus, we can divide the field-to-fuel life cycle of agricultural residue-based biofuels into five high-level and relatively independent sub-stages: 1) production of agricultural residues, which includes land occupation and the consumption of energy, fertilizer, and pesticides; 2) collection of agricultural residues, which involves the collection radius and energy consumption; 3) conversion of agricultural residues to biofuels, which include liquid fuels, briquettes, and gaseous fuels; 4) biofuel distribution, which includes vehicle, train, ship, and pipeline transportation; and 5) biofuel usage, which includes vehicle fuel consumption, heating and/or cooling, and electricity generation. These five sub-stages can then be grouped into the feedstock, fuels, and utilization stages (Fig. 1). Although they are different sub-stages, the production and collection of agricultural residues share common characteristics (Fig. 1). The conversion and distribution sub-stages in the fuels stage have different transformation technologies, and several methods are available for the utilization stage (Fig. 1).

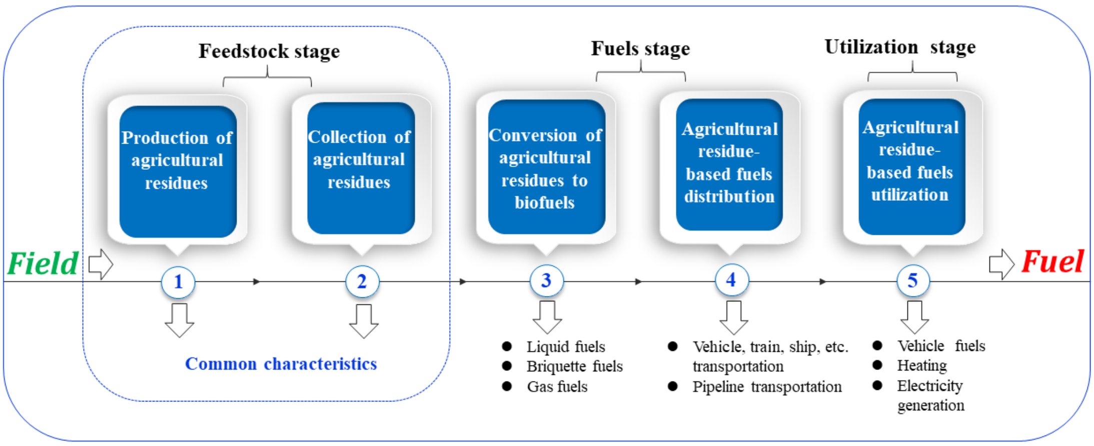

Fig. 1. Main life cycle stages of agricultural residue-based biofuels.

3. Production of agricultural residues

Before a biomass fuel production plant can be commissioned, a comprehensive database that includes information on residue production, consumption of energy, fertilizers, and pesticides, and land occupation must be in place.

3.1. Agricultural residues-to-grain weight ratio

The agricultural residues-to-grain weight ratio compares the occurrence of agricultural residues to grain yield and represents the production of agricultural residues. The ratio varies among crop areas and type. The agricultural residues-to-grain weight ratio should be analyzed over different seasons and across growing regions. Once this database is established, the ratio distribution for different crops can be mapped.

Before establishing a fuel conversion plant, it is important to ensure that abundant feedstock is available. Feedstock amount can be calculated from the grain yield, cultivation area, and agricultural residues-to-grain weight ratio. When agricultural residues are used to produce fuels, the energy use availability of the agricultural residues is calculated by Eq.(1) :

$$J = \sum_{i=1}^{n} S_i Y_i \theta_i \eta_i \tag{1}$$

where J is the total amount of agricultural residues available for fuel production (ton/yr); S_i is the cultivation area for the i^{th} crop (km^2/yr); Y_i is the grain yield of the i^{th} crop (ton/km$^2\cdot$yr); θ_i is the agricultural residues-to-grain weight ratio of the i^{th} crop (kg/kg); and η_i is the energy use availability of the i^{th} agricultural residue (%).

3.2. LCA allocation during plant growth

Value-based allocation methods such as energy and economic allocation are considered appropriate for reflecting production goals. In economic markets, economic values shape system formation. However, because product prices can change, economic allocation leads to temporal variability in study outcomes even when the production system remains unchanged[22].

In general, there are three main approaches for determining LCA allocation during plant growth or production (Fig. 2): 1) all impacts are allocated to the grain, and agricultural residues are considered waste; 2) half of total impacts are allocated to the grain, and half to agricultural residues; and 3) impacts are allocated to different system components according to agricultural residues-to-grain price (revenue) and weight ratios. Although grain and agricultural residue prices may fluctuate, the agricultural residues-to-grain weight ratio is relatively stable.

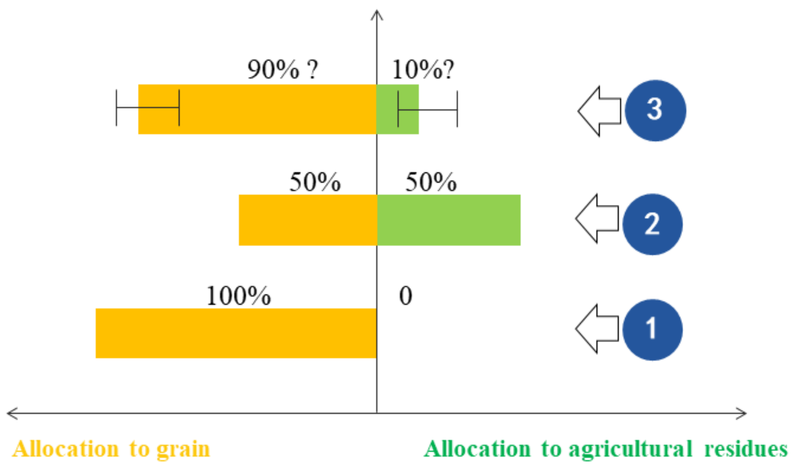

Fig. 2. Three approaches to allocation during crop growth or production (Error bars represent fluctuations in grain and agricultural residue prices).

Approach 1: In this approach, all impacts are allocated to the crop grain, and agricultural residues are considered waste[29]. However, with the development of new technology, increasing amounts of agricultural residues are being recycled and reused, such as for fuel, fertilizer, and feed production, as well as for biochemical processes. Therefore, this approach does not accurately assign allocations to agricultural residues.

Approach 2: In this approach, environmental impacts are evenly allocated between the crop grain and agricultural residues. However, this allocation method can inflate the value of agricultural residues, which negatively affects their use. Thus, this approach is also not ideal.

Approach 3: In this approach, allocation is based on the economic values of the grain and agricultural residues, and also their weight ratio. Other parameters such as carbon sequestration benefits and utilization scale are considered as well to estimate the allocation ratio.

3.3. Considerations for multifactorial allocation

According to Approach 3, allocation should be based on factors such as agricultural residues-to-grain weight and price ratios, energy consumption (e.g., diesel, electricity), land occupation, irrigation, and consumption of fertilizers, herbicides, and pesticides.

Corn grown in Henan Province, China, has an agricultural residues-to-grain weight ratio of 1.2, and the price of corn grain is 10 times that of the price of cornstalks. Thus, corn grain and cornstalks generate approximately 89.2% and 10.8% of total revenue, respectively (Fig. 3).

Accordingly, allocation percentages for the grain and agricultural residues during the production of residues would be 89.2% and 10.8%, respectively. Prices for grain and agricultural residues can be averaged over the last three years. Relative consumption during plant growth can be estimated from mean consumption over the last three years or from the LCA database.

In addition, the amount of carbon dioxide (CO_2) absorbed during biomass growth and the amount emitted during the feedstock stage should be calculated. This would illustrate the CO_2 sources and sinks along the supply chain for agricultural residue-based biofuels and highlight potential opportunities for carbon capture and storage[30] to mitigate future CO_2 emissions.

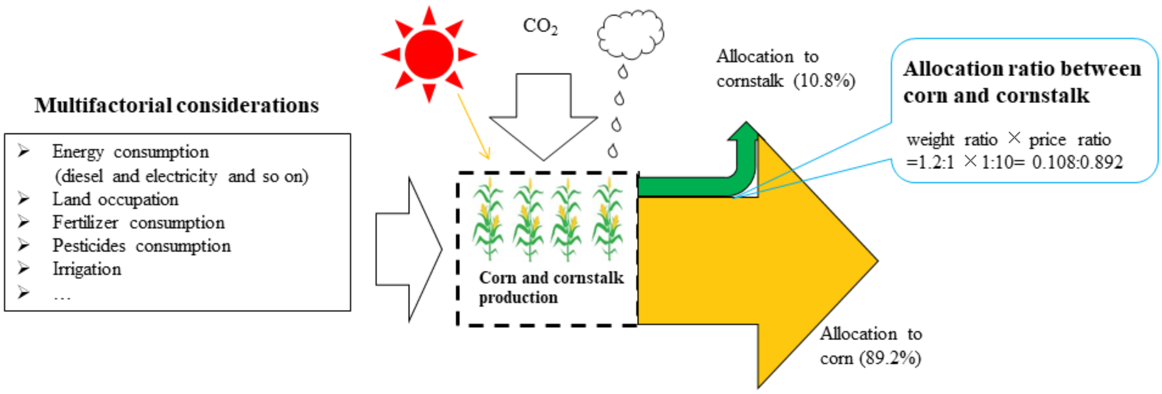

Fig. 3. Allocation based on weight and price ratios during the production of agricultural residues.

4. Collection of agricultural residues

During this process, the collection radius, energy consumption, and emissions should be considered. Before the collection radius can be calculated, the arable land area coefficient of the crop and the energy use availability coefficient of the agricultural residues must be confirmed.

4.1. Arable land area coefficient

The availability of agricultural residues varies spatially and temporally[31]. The arable land area coefficient of a particular crop is considered one of the main characteristics of agricultural residues. Geographical Information Systems (GIS) are spatial tools that enable the precise assessment of the distribution of renewable energy resources to facilitate decision-making. GIS models can be used to optimize the number of satellite storage areas, the geographic distribution of these storage areas and their respective collection areas, and the location of the energy plants that would use agricultural residue-based biofuels[32]. GIS and aerographic mapping can be used to study crop planting over space and time. Useful information includes crop species, harvest area in summer or fall, crop area for different species, and the ratio of crop area to total land area. From this information, crop area as a percentage of total land area, total crop area, and crop harvesting times can be determined. The species and area covered by crops planted for summer or fall harvests affect how agricultural residues are collected. Overall, the arable land area coefficient is based on temporal and spatial variation in crop planting (Fig. 4).

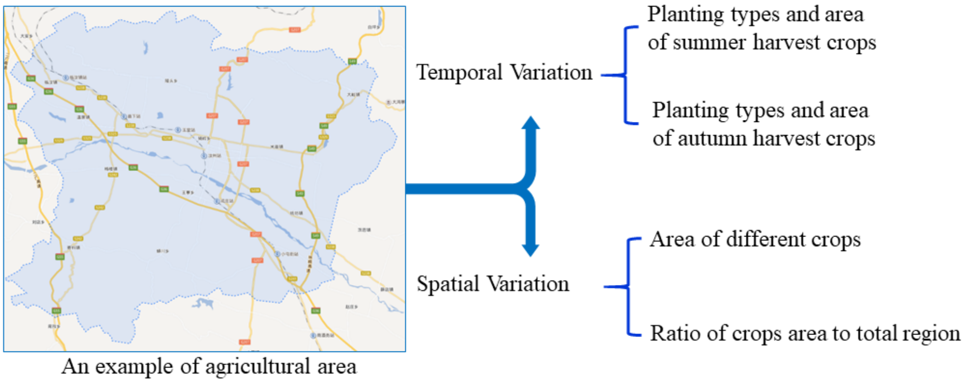

Fig. 4. Arable land area coefficient based on temporal and spatial variation in crop planting.

4.2. Energy use availability coefficient

The energy use availability coefficient should be calculated before agricultural residues are used for biofuel production, and is key to estimating the collection radius of agricultural residue-based biofuels (Fig. 5). Agricultural residues tend to have low energy density. However, in addition to energy generation, agricultural residues can be consumed in other ways. For example, agricultural residues can be used as fertilizers, forage, and industrial raw materials. Wheat straw and corn stalks can be used as fertilizer and forage; rice straw as forage and industrial materials; cotton stalks for energy generation; peanut shells, leaves, and tubers as forage; bean stems and leaves as forage and fuel; and vegetable residues as fertilizer and forage[33]. Agricultural residues can garner higher prices when they are used as industrial raw materials and forage as well, such as wheat straw being used for pulp and paper production. The amount of agricultural residues that are not used for energy generation should be subtracted from calculations during LCA. In the circle of Fig. 5, red indicates the proportion of agricultural residues that could be used for energy generation, whereas gray indicates the proportion that could be used as fertilizers, forage, and industrial raw materials. The latter proportion should be subtracted from calculations during LCA.

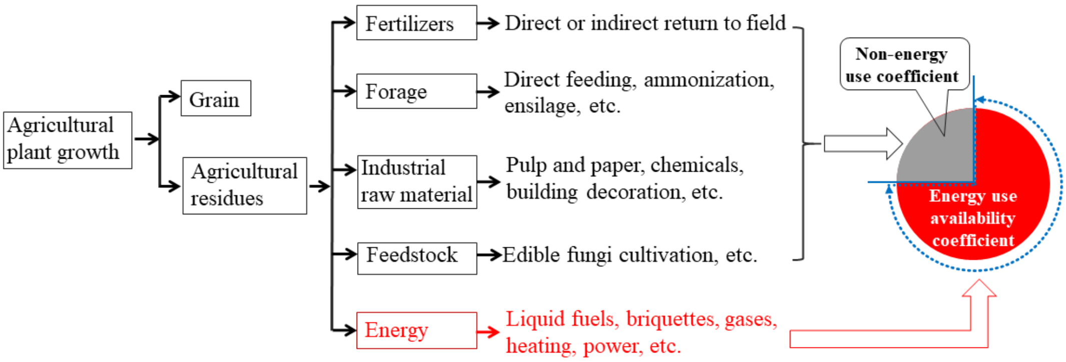

Fig. 5. Energy use availability coefficient of agricultural residues.

4.3. Collection radius of agricultural residues

The collection radius, i.e., the transportation distance between the location of the agricultural residues and the biofuel conversion plant, depends on how well developed the road network is, the scale of the biofuel conversion system, annual consumption rate of agricultural residues, agricultural residues-to-grain weight ratio, energy use availability coefficient, and arable land area coefficient. The collection radius seldom follows a straight line; calculations must account for road patterns and biofuel plant location (Fig. 6). Road travel distances can be calculated using a GIS map. Here, different kinds of collection radius of the agricultural residues are listed in Fig.6. (a) Actual collection radius *R'* can be calculated by adding *L*, the distance between the biofuel plant and the center of the crop area, to estimate collection radius *R*. (b) The actual transportation route follows a zigzag pattern (S_1, S_2, and S_3) instead of a straight line. Thus, $R' = S_1 + S_2 + S_3$. (c) The methods used in (a) and (b) can be combined to calculate *R'*.

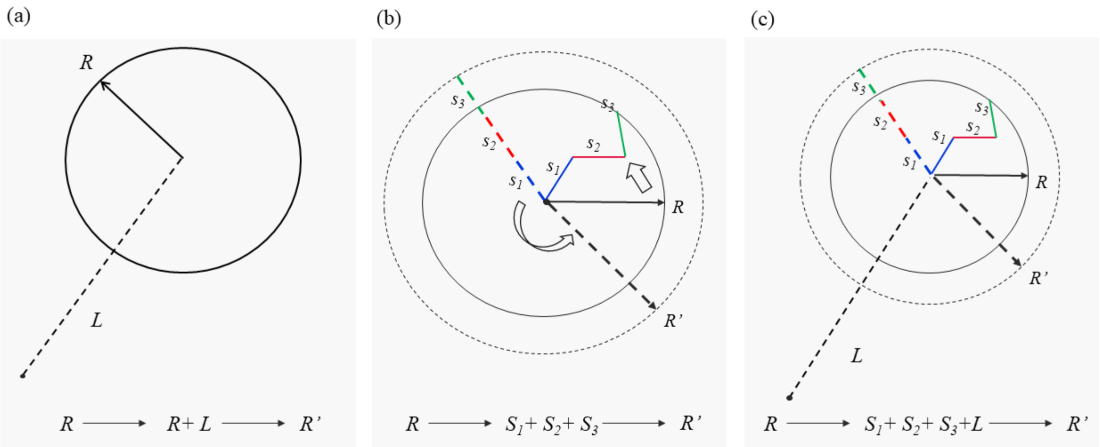

Fig. 6. Three ways of calculating the collection radius between the location of the agricultural residues and the biofuel plant.

The collection radius R (km) can be calculated using the equation below:

$$Z = \pi R^2 = P_y / Y\theta\eta\xi\lambda \tag{2}$$

where Z is the collection area for the agricultural residues (km^2); P_y is annual consumption rate of agricultural residues (ton/yr); Y is annual grain yield (ton/km^2·yr); θ is agricultural residues-to-grain weight ratio (kg/kg); η is the energy use availability of the agricultural residues (minus the residues used as fertilizers, forage, industrial materials, and feedstock for edible fungi); ξ is the coefficient of cultivated land which accounts for the local region ratio among the agricultural residue-based fuel plant; and λ is the coefficient of particular agricultural residues cultivated land (cultivated land area of particular agricultural residues for producing biofuel accounts for the total crop cultivated land area).

Here, we use a briquette fuel plant in Henan Province, China, that produces 10,000 metric tons of fuel per year as an example. Cornstalks are used as the feedstock material. P_y is approximately 10,700 ton/yr; Y is 750 ton/km^2·yr; θ is 1.2; η is 0.4; ξ is 0.7; and λ is 0.7. According to Eq. (2), the calculated collection radius R of this plant is approximately 4.39 km. The distance from the biofuel plant to the center of the corn planting area is approximately 2 km. Thus, the actual collection radius is R' = 4.39 km + 2 km = 6.39 km.

4.4. Emissions related to collection of agricultural residues

Vehicle and transportation parameters related to oil consumption can be calculated as follows, assuming the hypothetical transportation distance ratio with no load and a full load is 1:1[34,35]:

$$\left[g_1\left(L/2v_1\right)+g_0\left(L/2v_0\right)\right]N_{en}\Big/\left[m\left(L/2\right)\right]=\left(g_1/v_1+g_0/v_0\right)\left(N_{en}/m\right)=q \tag{3}$$

where g_1 is unit fuel consumption with varying loads (except 0) on a specific road (kg/kWh); g_0 is unit fuel consumption with no load on a specific road (kg/kWh); v_1 is mean vehicle speed with varying loads (except 0) on a specific road (km/h); v_0 is mean vehicle speed with no load on a specific road (km/h); N_{en} is vehicle power (kW); m is vehicle weight rating (10^3 kg); L is mean transport distance of a single vehicle (km); and q is oil consumption per km and per kg of the vehicle (kg/kg·km). Mean transport distance L is calculated as twice the actual collection radius, i.e., $L = 2R'$.

The vehicle weight rating is related to vehicle power[30], as a larger m is correlated with a larger N_{en}. The ratio of vehicle power to weight rating is expressed as $k_n = N_{en}/m$. The quantity of heat produced from the diesel consumed by an average vehicle is calculated as follows:

$$Q_o = qLm'E_o \tag{4}$$

where Q_o is the quantity of heat produced from oil consumed by an average vehicle (MJ); m' is the mean vehicle load (kg); and E_o is the low heating value of diesel (MJ/kg).

The oil consumption for collection of agricultural residues can be calculated using Eqs. (3), (4). Calculations of emissions from the transport vehicle can then be based on oil consumption rates. Energy consumption and emissions due to vehicular transportation can vary according to vehicle and road types and conditions. For example, whether roads are paved with cement, sand, or asphalt, or whether vehicles are empty or carrying half or full loads. These variations should be reflected in emissions databases. In addition, the total time vehicles are in use for the collection and transportation of agricultural residues during the entire biofuel life cycle should be determined. By considering all of these factors, energy consumption and emissions per unit distance of the vehicles used for collecting agricultural residues can be calculated.

5. Determining system boundaries

The consideration of the boundaries of the feedstock production and collection stages usually includes factors such as energy consumption, land occupation, and fertilizer input. Additional factors that may be considered include seed cultivation, human labor inputs, and vehicle manufacturing (Fig. 7). Ideally, the boundary conditions would cover the maximum number of boundary factors that can be considered within reasonable time constraints. In general, factors that are classified similarly and those with an overall proportion of 0.1% or less can be neglected. The factors within Boundary 1 must always be considered, whereas those within Boundary 2 are considered on a case-by-case basis (Fig. 7).

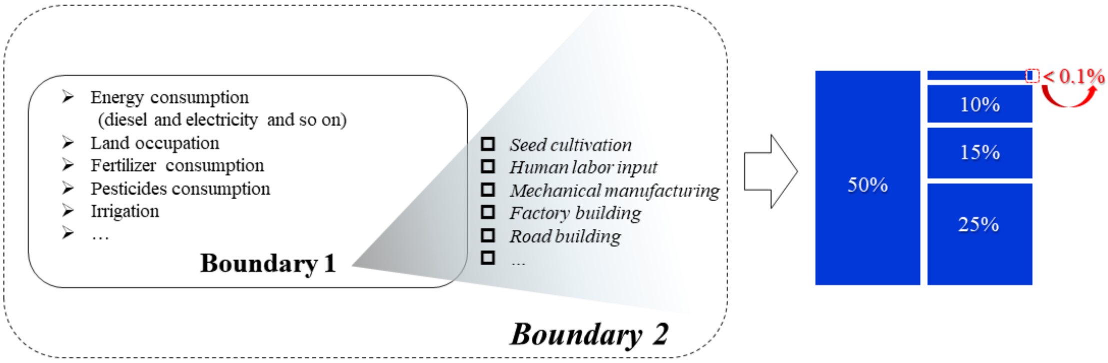

Fig. 7. Determining LCA system boundaries during the feedstock stage for agricultural residue-based biofuels.

6. Benefits of emissions reduction

The production of biofuels from agricultural residues helps to reduce waste, but the overall environmental and ecological benefits of this process still need to be determined. Cereal fields in northern China can yield two crops every year or three crops every two years. Due to fast turnover, the time interval between harvesting and planting is short. Fields must be cleared and the straw must be used before the next round of planting. If not, agricultural residues may be burned directly in the fields. Direct burning leads to increases in emissions of fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and greenhouse gases. Hence, using agricultural residues for biofuels is a better alternative to open burning.

The open burning of agricultural residues contributes 20.8% of the atmospheric pollutants in China[36]. Most of these residues, approximately 87%, are composed of rice, wheat, and corn stalks[36]. According to the emission factors for agricultural residues open burning (see as Table 1), in a province of China in 2014, the amount of wheat straw open burning had been reached to 1.25×10^7 tons. The burning of wheat straw produced 9.5×10^4 metric tons of $PM_{2.5}$, 1.1×10^4 metric tons of SO_2, 4.1×10^4 metric tons of NO_x, 7.5×10^5 metric tons of CO, 0.5×10^4 metric tons of ammonia (NH_3), 4.3×10^4 metric tons of methane (CH_4), 9.3×10^4 metric tons of non-methane volatile organic compounds (NMVOCs), and 1.83×10^7 metric tons of carbon dioxide (CO_2). The amount corn stalk open burning had been reached to 7.35×10^6 metric tons. The burning of corn stalk produced 8.6×10^4 metric tons of $PM_{2.5}$, 0.3×10^4 metric tons of SO_2, 3.2×10^4 metric tons of NO_x, 3.9×10^5 metric tons of CO, 0.5×10^4 metric tons of NH_3, 3.2×10^4

metric tons of CH_4, 7.3 × 10^4 metric tons of NMVOCs, and 9.9 × 10^6 metric tons of CO_2. Additionally, the amount rice straw open burning had been reached to 9.7 × 10^5 metric tons. The burning of rice straw produced 1.3 × 10^4 metric tons of $PM_{2.5}$, 0.1 × 10^4 metric tons of SO_2, 0.3 × 10^4 metric tons of NO_x, 3.4 × 10^4 metric tons of CO, 0.1 × 10^4 metric tons of NH_3, 0.3 × 10^4 metric tons of CH_4, 0.6 × 10^4 metric tons of NMVOCs, and 1.4 × 10^6 metric tons of CO_2.

Table 1. Emissions produced by the open burning of agricultural residues[36,37].

Crops	Emission factors/(g/kg)							
	$PM_{2.5}$	SO_2	NO_x	CO	NH_3	CH_4	NMVOC	CO_2
Wheat	7.60	0.85	3.30	60.00	0.37	3.40	7.50	1460.00
Corn	11.70	0.44	4.30	53.00	0.68	4.40	10.00	1350.00
Rice	12.95	0.90	3.10	34.70	0.78	3.20	6.05	1460.00

As the open burning and collection of agricultural residues occurs during the feedstock stage, benefits accrued from emissions reduction should be considered for this stage. Scenarios in which agricultural residues are burned directly could be compared to those in which residues are used as biofuels. Comparisons should be based on the same unit used to measure agricultural residue biomass. Scenarios in which agricultural residues are used as biofuels could be considered the baseline. Environmental impacts during the feedstock stage, such as pollutant emissions, can be estimated from the LCA of agricultural residue-based biofuels. Emissions from open burning of agricultural residues can be obtained from direct investigations. These data can then be used to calculate the reduction in emissions when agricultural residues are converted to biofuels instead of being burned. With this knowledge, the use efficiency of agricultural residues can be enhanced to reduce air pollution (Fig. 8). Nevertheless, field studies must be conducted to accurately determine actual reductions in open burning due to the diversion of agricultural residues toward biofuel production. Furthermore, open burning negatively impacts the soil and water, and these effects must be accounted for.

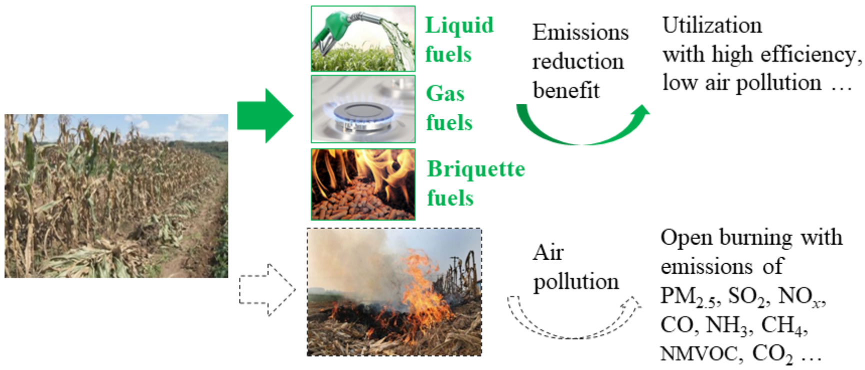

Fig. 8. Emission of atmospheric pollutants can be reduced by diverting some of the agricultural residues toward biofuel production.

7. Conclusions

In this paper, we discussed the common LCA characteristics of agricultural residue-based biofuels during the feedstock stage, which comprises the processes of producing and collecting agricultural residues. Allocation can be carried out according to agricultural residues-to-grain price and weight ratios. For corn, the allocation percentages for the production of corn grain and corn stalks (agricultural residues) were approximately 89% and 11%, respectively. Collection radius is calculated based on the arable land area coefficient of the crop and energy use availability coefficient. During the collection process, emissions depend on the collection radius, and road and vehicle load conditions. We also discussed the factors that should be considered to determine optimal system boundaries. The conversion of agricultural residues to biofuels not only increases the use efficiency of the residues but also reduces air pollution, generating environmental benefits.

Future research should focus on collecting data from the feedstock stage. An analysis of common LCA characteristics of large-scale production of agricultural residue-based biofuels can help guide the further development of the biofuel production process.

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